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Large flattened mode airclad photonic crystal fibers

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6. AUTHOR(S)

Dr. René E Kristiansen

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Crystal Fibre A/S
Blokken 84
Birkerod 3460
Denmark

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

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EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SPC 06-4007

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking Crystal Fibre A/S as follows: TECHNICAL PROPOSAL/DESCRIPTION OF WORK:
TASK 1: Crystal Fibre will conduct research and development of large flattened mode area, dual clad multi-core Yb-doped photonic crystal fiber with designs and specifications to be provided by the US Air Force. The intention is to do three fiber types each fiber type to be done in both a passive and active (Yb doped) version totally 6 (six) fibers. The third fiber type is intended to be a tuned cladding type with two differently sized airholes in the inner cladding. Depending on the outcome of the second fiber type (19 cell), the third fiber type might be changed to be a second iteration of the 19 cell fiber without tuned cladding.The fiber may be polarization maintaining (PM) and will be dependent on the requirements of the US Air Force. Nominal fiber designs will include 7 and 19 cell core fibers with nominal specifications of 380 micron 0.6 NA pump core, and signal core diameters to be defined. Crystal Fibre shall fabricate and deliver 1 pre-form worth but not less than 50 meters of passive and active versions of each fiber designed under this task.
TASK 2: Crystal Fibre shall provide characteristics of the fiber fabricated to include core and cladding diameters, core and cladding numerical apertures, Yb doping concentration, and pump absorption at 976nm.
Design ideas/proposals/specifications will be exchanged whenever needed. Deliverables are fiber samples and fiber characterization reports following each fiber sample delivery. Deliveries are expected with approximately 8 week intervals.

15. SUBJECT TERMS
EOARD, Laser physics, Fibre Lasers

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CRYSTAL FIBRE

FINAL REPORT FA8655-06-C-4007

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Agreement No.:	FA8655-06-C-4007
Recipient's Name:	Crystal Fibre A/S
Recipient's Address:	Blokken 84, DK-3460 Birkerød Denmark
Date:	7 May 2007
Customer organization:	Air Force Research Laboratory,
AFRL/KirtlandCustomer contact:	Capt. Benjamin G. Ward
Project Manager:	Kim P. Hansen (kph@crystal-fibre.com)
Measurements by:	Anders Petersson and Laurent J. G. Fillon
Fiber:	Yb-doped LFM fiber

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Measurements completed 16.05.2007.

Kim P. Hansen

ITEM 0001 – FIRST ITERATION FIBER

Fiber IDs:	Passive: 060906-CF0743 Active: 060911-CF0747
Delivered fiber length:	Passive: 80 m Active: 70 m

PHYSICAL PROPERTIES – PASSIVE FIBER:	FIBER	TARGET
MATERIAL		
Core material:	F-doped silica	
Cladding material:	Pure silica	
Coating material:	High temperature acrylate (single layer)	
DIMENSIONS		
Core diameter:	35 µm	35 µm
Pitch	10 µm	10 µm
d/pitch	Fiber 1: 0.33	0.35
	Fiber 2: 0.27	0.30
	Fiber 3: 0.39	0.40
Cladding diameter:	615 µm	600 µm +/- 50 µm
Coating diameter:	725 µm	

OPTICAL PROPERTIES – PASSIVE FIBER:	FIBER	TARGET
SIGNAL CORE:		
Core Δn:	$-8{\cdot}10^{-4}$ – $-9{\cdot}10^{-4}$ nm	$-8.5{\cdot}10^{-4}$ +/- $0.5{\cdot}10^{-4}$
B-doped SAPS Δn:	$-6{\cdot}10^{-3}$	< $-3{\cdot}10^{-3}$
Birefringence @ 1060 nm:	~$1{\cdot}10^{-4}$	

PHYSICAL PROPERTIES – ACTIVE FIBER:	FIBER	TARGET
MATERIAL		
Core material:	Yb-doped silica	
Cladding material:	Pure silica	
Coating material:	High temperature acrylate (single layer)	
DIMENSIONS		
Core diameter:	35 µm	35 µm
Pitch	10 µm	10 µm
d/pitch	Fiber 1: 0.30	0.30
	Fiber 2: 0.39	0.40
	Fiber 3: 0.35	0.35
Pump core diameter	325 µm	~300 µm
Cladding diameter:	617 µm	600 µm +/- 50 µm
Coating diameter:	721 µm	

OPTICAL PROPERTIES – ACTIVE FIBER:

	FIBER	TARGET
SIGNAL CORE:		
Core Δn:	~-8·10^{-4}	-8.5·10^{-4} +/- 0.5·10^{-4}
B-doped SAPS Δn:	-6·10^{-3}	‹ -3·10^{-3}
Birefringence @ 1060 nm:	~1·10^{-4}	
Mode field diameter @ 1060 nm	Fiber 1: 28.9 µm Fiber 2: 26.6 µm Fiber 3: 26.9 µm	
MULTIMODE PUMP CORE:		
Numerical aperture @ 975 nm[6]:	0.55-0.57	~ 0.55
Pump absorption @ 920 nm[7]:	~1 dB/m	
Pump absorption @ 976 nm[8]:	~3 dB/m	

[6]: Measured as the angle corresponding to FWHM of the maximum intensity.
[8]: Calculated as 3 times the absorption of 920nm.

FIBER STRUCTURE – PASSIVE FIBER

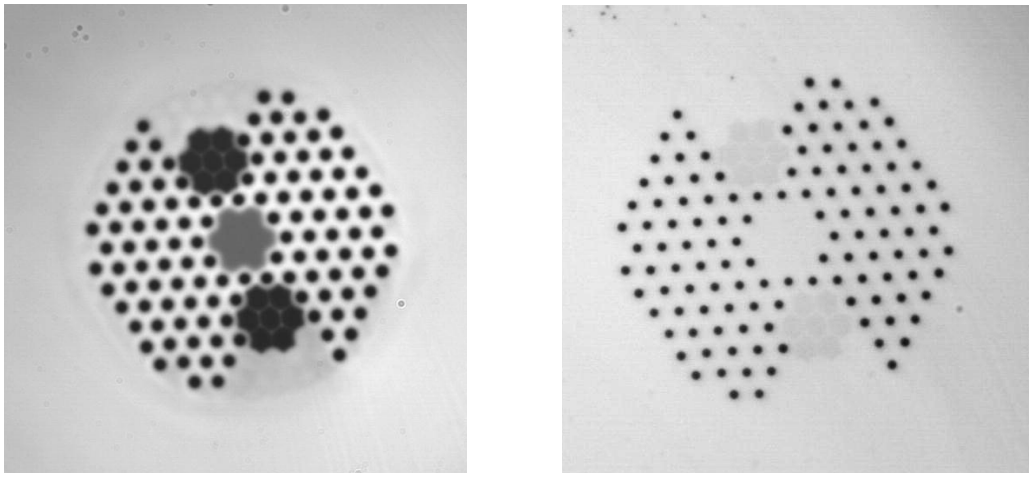


Figure 1 Back illuminated (left) and top illuminated (right) microscope pictures of the fiber cross section

FIBER STRUCTURE – ACTIVE FIBER

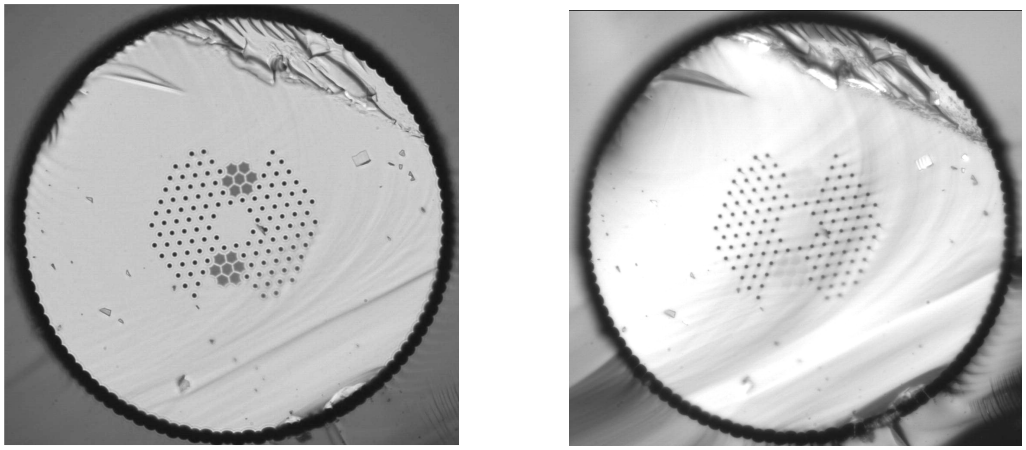


Figure 2 Back illuminated (left) and top illuminated (right) microscope pictures of the fiber cross section

MODAL PROPERTEIES – PASSIVE FIBER

The passive fibers are only very weakly guiding. When measured on a large standard spool (32 cm diameter), all fibers exhibit large attenuation at 1060 nm.

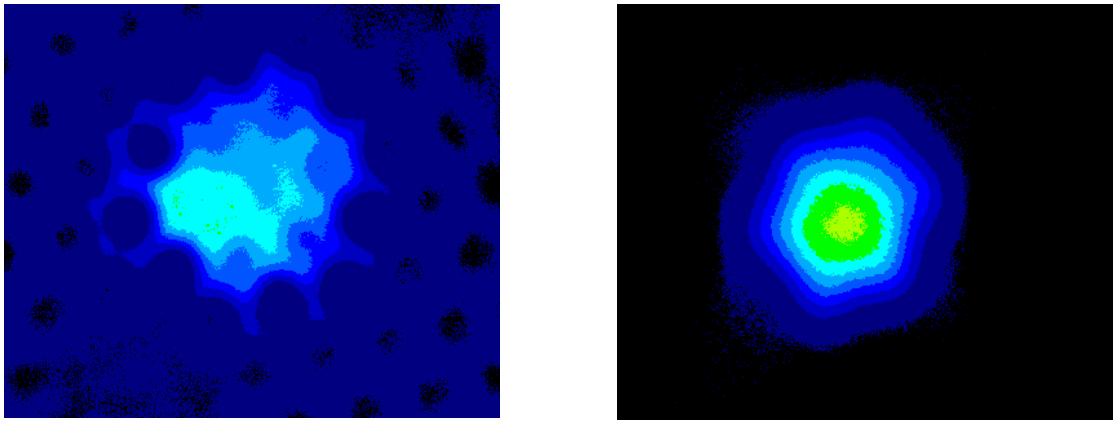


Figure 3 Near field of the best guiding fiber (fiber 3) at 1060 nm (left) and 1550 nm (right).

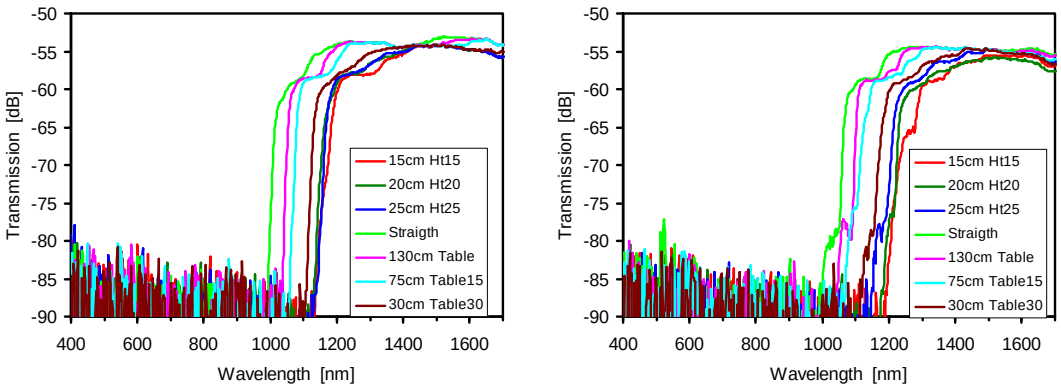
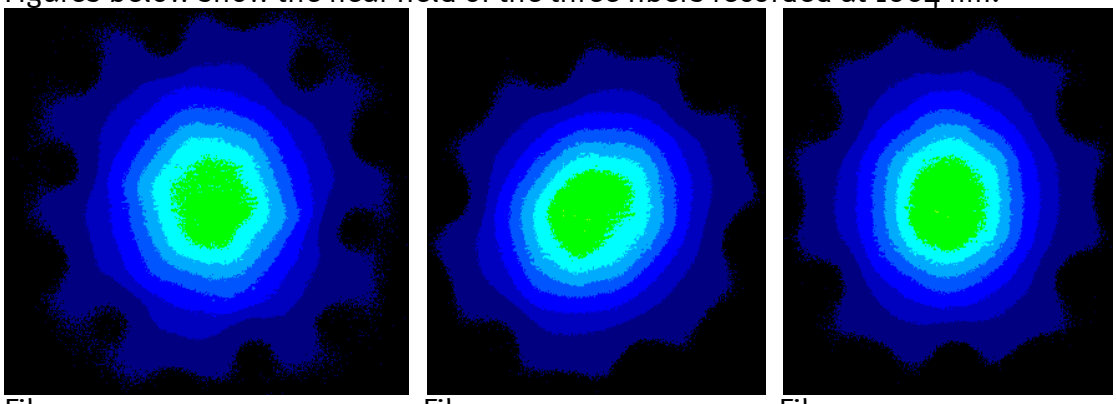


Figure 4 Transmission through fiber 3 for the two polarization directions. The legend refers to the bending diameter. At low wavelengths, the fiber do not transmit due to bending loss. Going to longer wavelength, the fibers transmits in one spatial mode (first plateau starting around 1 µm) and then goes multimode at longer wavelengths (transmission increases to new plateau). The transmission curves for the two polarizations are shifted in wavelength due to the birefringence, creating a polarizing region. Note the very narrow window between the bending loss edge and the multimode transition.

MODAL PROPERTIES – ACTIVE FIBER

Figures below show the near field of the three fibers recorded at 1064 nm.



Fiber 1 Fiber 2 Fiber 3

MFD (1/e2,1064nm):
Fiber 1 = 28.9 µm
Fiber 2 = 26.6 µm
Fiber 3 = 26.9 µm

Fiber 2 is multimode, even at small bending radii, as one can see by changing the launch conditions as below:

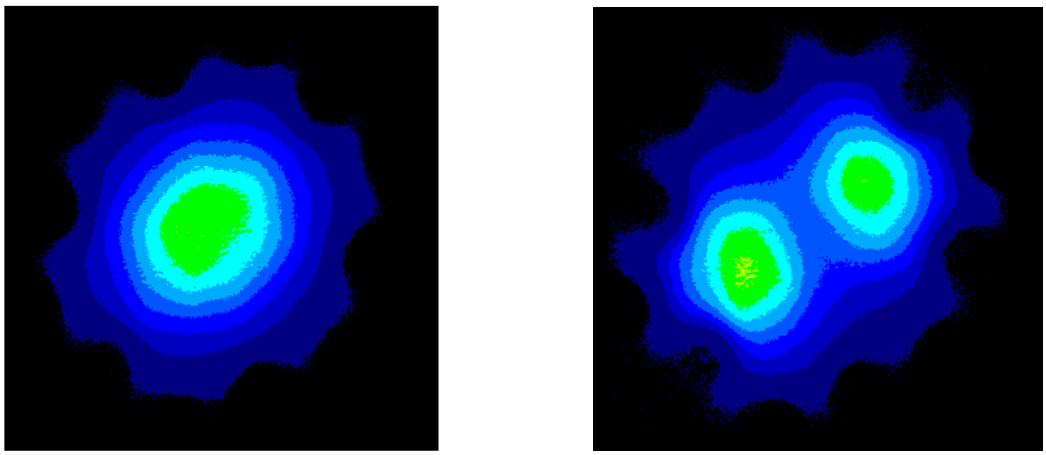


Figure 5 NF for fiber 2 with light launched in center (left) and on side of the core (right)

The aim of the fiber design is to flatten the mode compared to a standard Gaussian profile. Below is found the mode profile of fiber 1, which clearly features a non-Gaussian shape with a flat top.

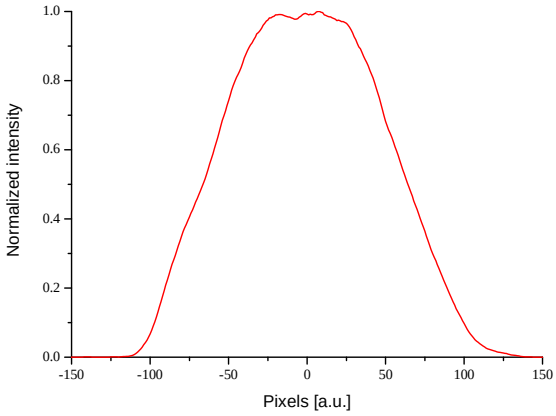


Figure 6 Mode profile of Fiber 1 at 1060 nm

Polarization dependent measurements of the transmission through the fibers are found below.

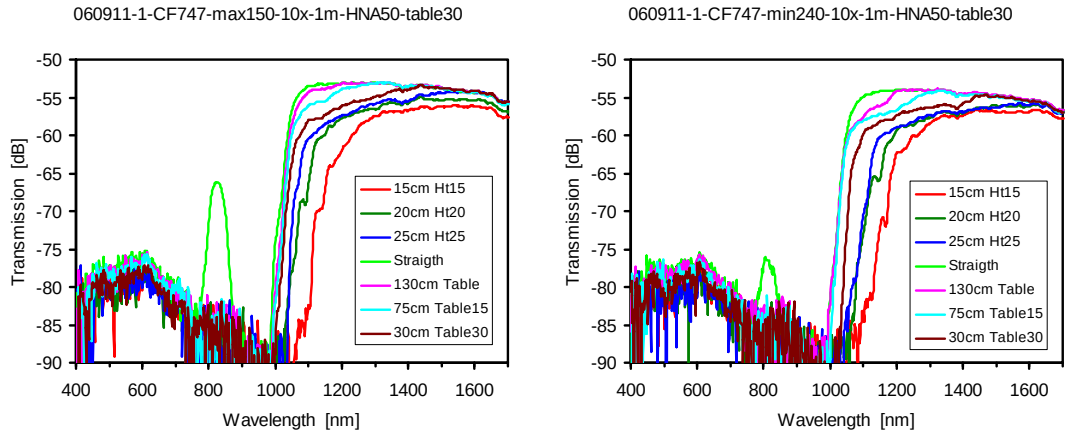


Figure 7 Transmission through Fiber 1 in the two polarization directions

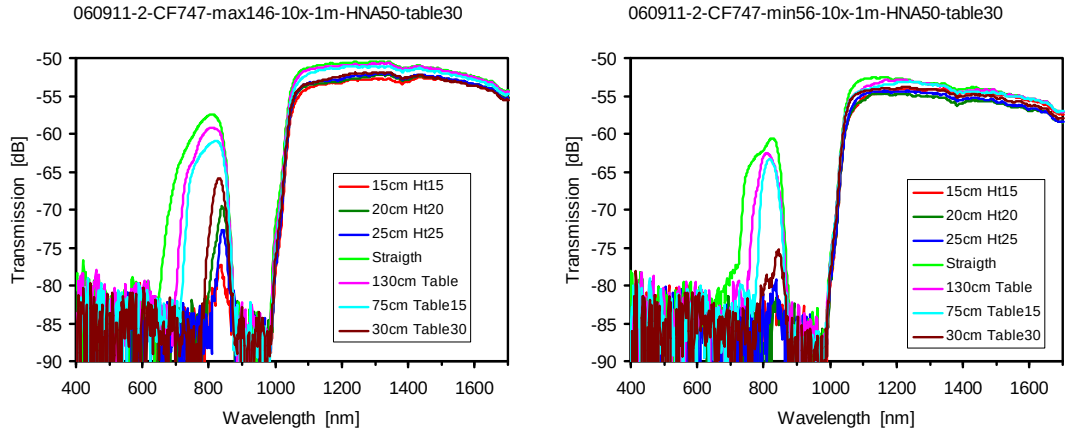


Figure 8 Transmission through Fiber 2 in the two polarization directions

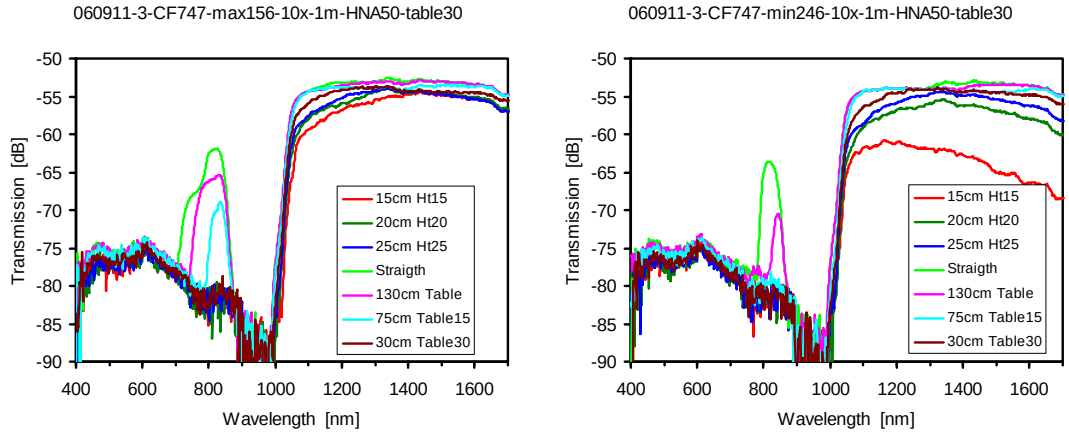


Figure 9 Transmission through Fiber 3 in the two polarization directions

GENERAL OBSERVATIONS

The down doping of the core has lead to reduced mode spacing. Consequently, the useful regime in which the fibers are guiding in a single mode with low loss has been reduced compared to normal undoped designs. The passive fibers have a core index, which is slightly below the active and the operational window is almost closed in the sense that the fiber exhibits large bending loss very close to the multimode transition wavelength.

ITEM 0002 – SECOND ITERATION FIBER

Fiber IDs: 061218-CF0818

Delivered fiber length: Fiber 1: ~20 m
Fiber 2: ~20 m
Fiber 3: ~20 m
Fiber 4: ~14 m

FIBER STRUCTURE – PASSIVE FIBER I

A total of 6 passive fibers was drawn to establish drawing conditions and preform designs suitable for the active fiber with two different hole-sizes.
The first batch of passive structure test fiber is constructed with one ring of 0.2 holes and six rings of 0.3 holes.

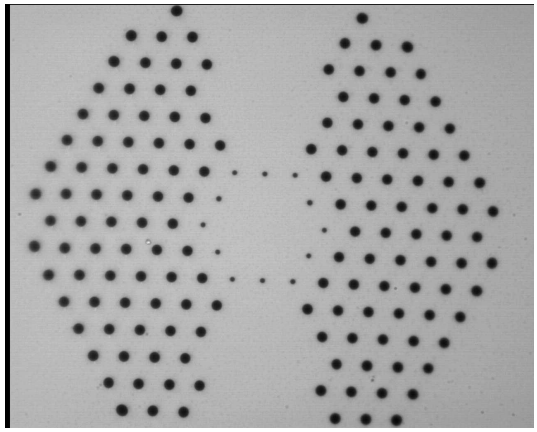


Figure 10 Top illuminated microscope pictures of the fiber cross section

The hole sizes on fiber level is found in the table below.

Fiber	Inner d/pitch	Outer d/pitch	Pitch
1	0.14	0.29	9.99 µm
2	0.175	0.35	9.95 µm
3	0.215	0.40	10.16 µm

FIBER STRUCTURE – PASSIVE FIBER II

The second batch of passive structure test fibers are made with three different hole-sizes in the cladding: one ring of 0.2 holes, three rings of 0.26 holes and three rings of 0.28 holes (on pre-form level).

The hole sizes on fiber level is found in the table below (the pitch is 10 µm).

Preform*		Fiber 1	Fiber 2	Fiber 3
0.2	Ring 1	0.16	0.19	0.2
0.26	Ring 2-4	0.28	0.31	0.33
0.28	Ring 5-7	0.32	0.36	0.37

* Indicating the hole size on preform level

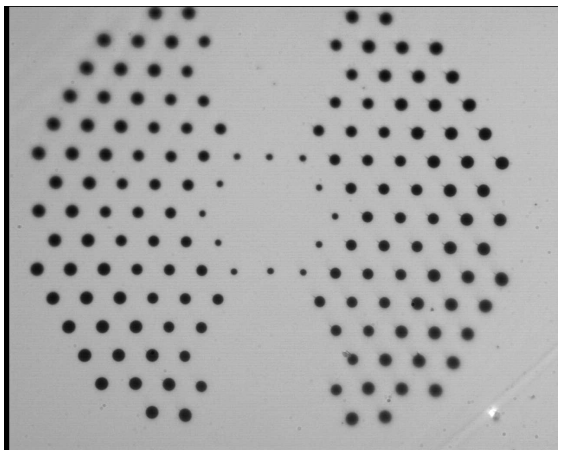


Figure 11 Top illuminated microscope pictures of the fiber cross section. The preform is constructed with one ring of 0.2 holes, three rings of 0.26 holes and three rings of 0.28 holes.

FIBER STRUCTURE – ACTIVE FIBER

The active fiber is produced using the results from the above shown passive test fibers. The final structure on fiber level is shown below.

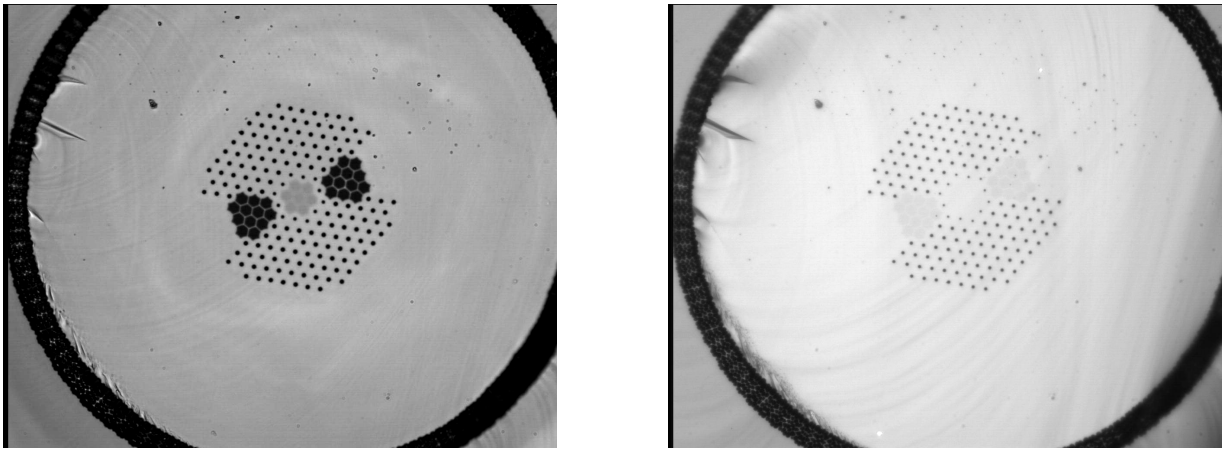


Figure 12 Back illuminated (left) and top illuminated (right) microscope pictures of the fiber cross section

PHYSICAL PROPERTIES – ACTIVE FIBER:

MATERIAL

Core material:Yb-doped silica
Cladding material: Pure and B-doped silica
Coating material: High temperature acrylate (single layer)

DIMENSIONS

Fiber	Pitch [µm]	Outer hole size	Inner hole-size	Pump core diameter [µm]	Cladding diameter [µm]	Coating di-ameter [µm]
1	9.9	0.30	0.21	425	940	1036
2	9.9	0.30	0.21	423	940	1036
3	10.1	0.35	0.25	425	940	1036
4	9.7	0.24	0.17	423	940	1036

OPTICAL PROPERTIES – ACTIVE FIBER:	FIBER	TARGET
SIGNAL CORE:		
Core Δn:	~$-7\cdot10^{-4}$	$-7\cdot10^{-4}$ +/- $1\cdot10^{-4}$
B-doped SAPS Δn:	$-6\cdot10^{-3}$	< $-3\cdot10^{-3}$
Mode field diameter @ 1060 nm	~33X36 µm	
MULTIMODE PUMP CORE:		
Numerical aperture @ 975 nm[1]:	0.65-0.7	> 0.50
Pump absorption @ 920 nm:	0.7 dB/m	
Pump absorption @ 976 nm:	2.2 dB/m	

[1]: Measured as the angle corresponding to FWHM of the maximum intensity.

MODAL PROPERTIES – ACTIVE FIBER

The modal properties of the fiber were investigated by monitoring the near field while bending the fibers. Fiber 1-3 are all multimode when bend to 45 cm diameter. Further bending was not tried due to the large outer diameter of the fibers.
Fiber 4 is slightly multimode when straight, but single mode when bend to a diameter of approximately 130 cm (see Figure 13). The near field (shown in Figure 14) shows a very flat non-Gaussian mode profile.

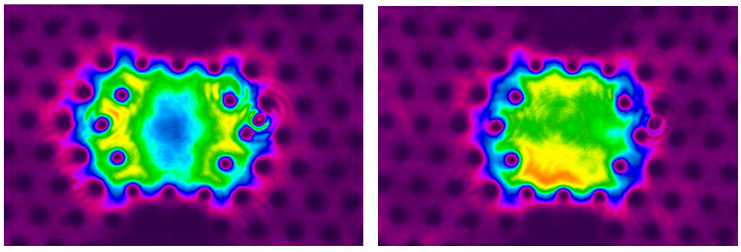


Figure 13 Near field of Fiber 4 in straight state (left) and bend to ~130 cm diameter (Right)

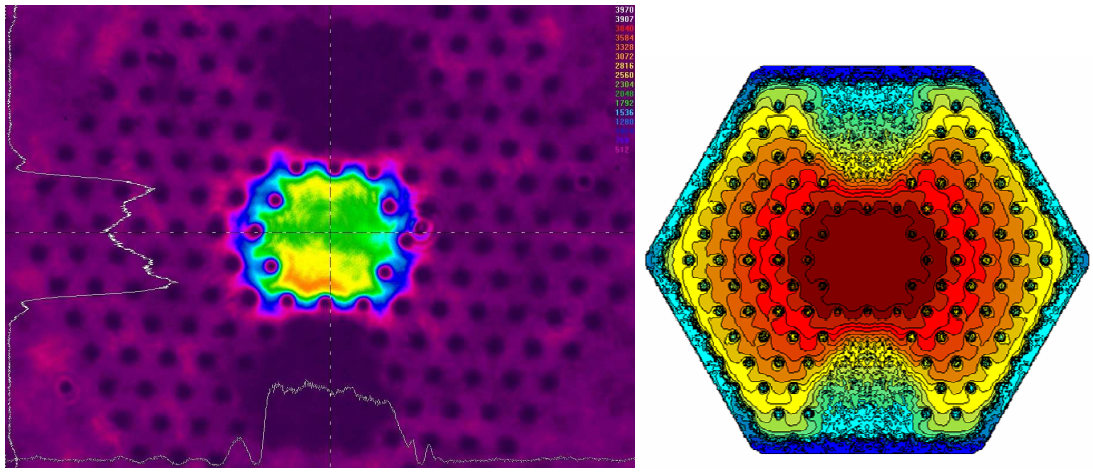


Figure 14 (Left) Near field of Fiber 4 bend to ~130 cm diameter. (Right) Simulated mode profile of target fiber.

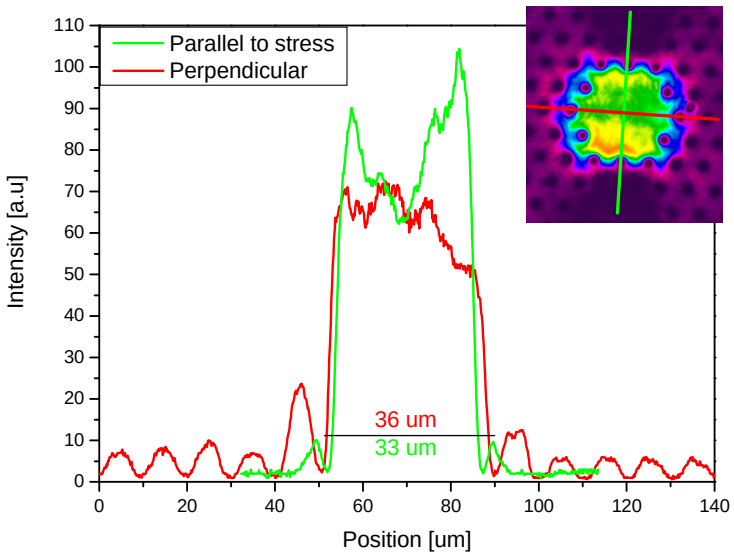


Figure 15 Mode profile (measured at 1060 nm) of Fiber 4 bend to ~130 cm diameter.

ITEM 0003 – THIRD ITERATION FIBER

Fiber IDs:	070503-CF0867 (pull 1,2,3,5)
Delivered fiber length:	65 m

PHYSICAL PROPERTIES:	FIBER	TARGET
MATERIAL		
Core material:	Yb and F co-doped silica	
Cladding material:	Pure silica	
Coating material:	High temperature acrylate (single layer)	
DIMENSIONS		
Inner cladding (pump core) diameter[1]:	433 µm	~430 µm
Cladding diameter:	960 µm	~900 µm
Coating diameter:	1045 µm	-
Inner hole size:	0.20	0.20
Outer hole size:	0.25	0.25
Pitch:	10 µm	10 µm

OPTICAL PROPERTIES:	FIBER	TARGET
SIGNAL CORE:		
Core Δn:	~$-7\cdot10^{-4}$	$-7\cdot10^{-4}$ +/- $1\cdot10^{-4}$
B-doped SAPS Δn:	$-6\cdot10^{-3}$	< $-3\cdot10^{-3}$
MULTIMODE PUMP CORE:		
Numerical aperture @ 975 nm[2]:	0.65-0.67	> 0.50
Pump absorption @ 920 nm:	0.7 dB/m	
Pump absorption @ 976 nm:	2.2 dB/m	

[1]: Measured as diameter of the largest inscribed circle within the inner cladding layer.
[2]: Measured as the angle corresponding to FWHM of the maximum intensity

FIBER STRUCTURE

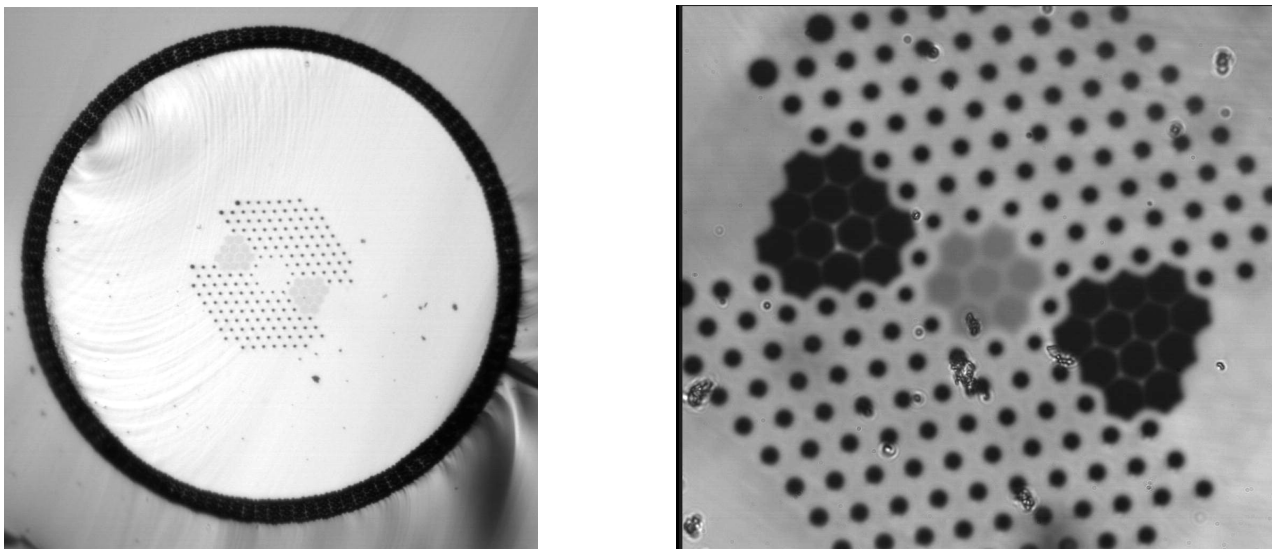


Figure 16 Optical microscope picture of fiber cross section. Right picture shows the structure illuminated from the back whereby the index differences between core, cladding and SAPS areas are visible.

NEAR FIELD

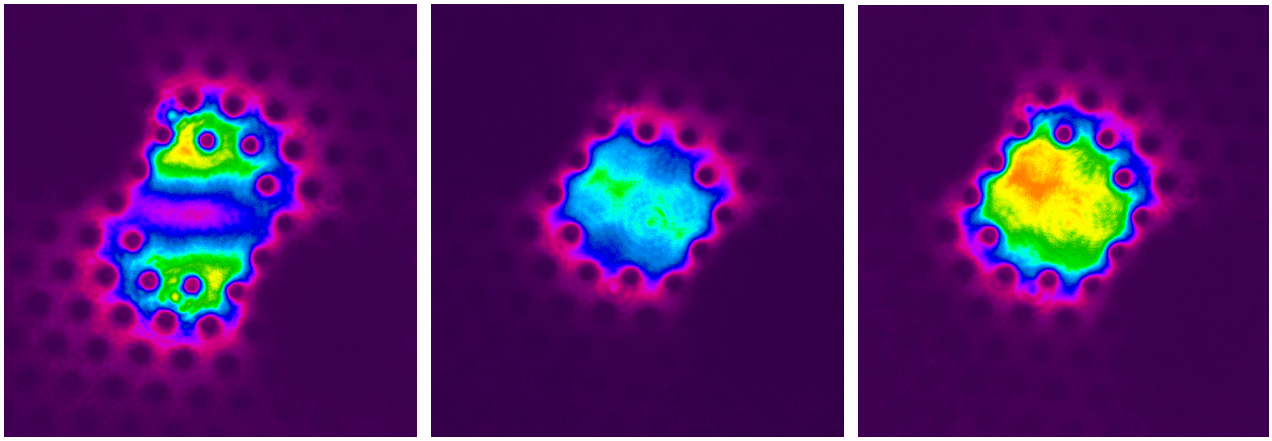


Figure 17 Near field recorded at 1060 nm. Left: 4 cm over table, Middle: 2 cm over table, Right: 1 cm over table (see figure below for test setup). The fiber is multimode in the two first positions but single mode in the last position 1 cm over the table.

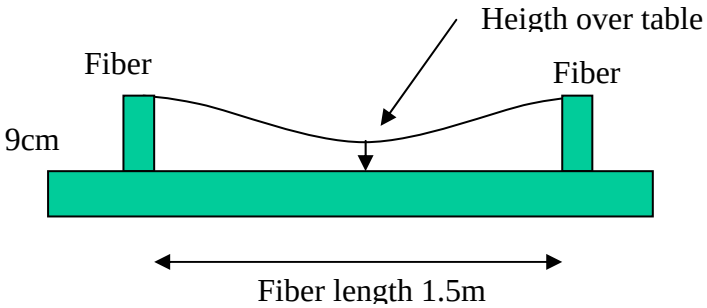


Figure 18 Near field test setup

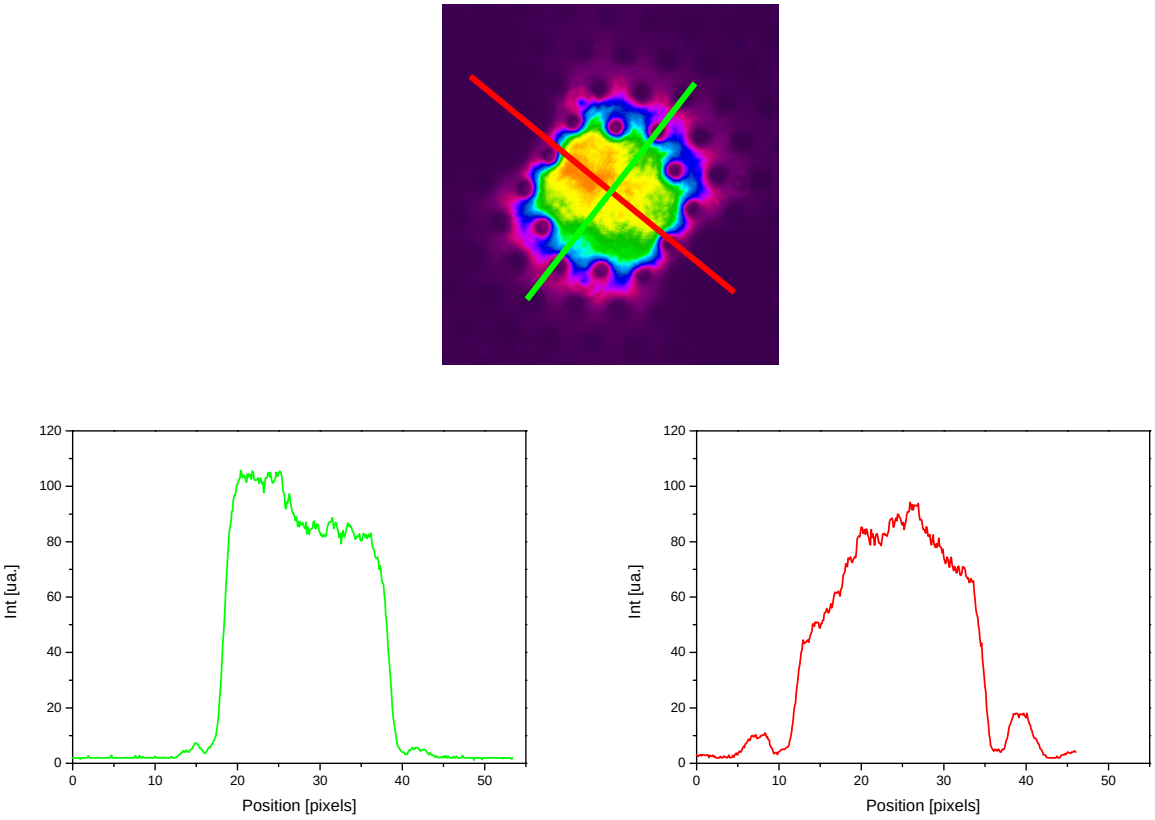


Figure 19 Mode profiles at 1060 nm in the two orthogonal directions (indicated by the colour)